Patent Application of

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for

FATIGUE MEASUREMENT DEVICE AND METHOD

FEDERALLY SPONSORED RESEARCH

Not Applicable

SEQUENCE LISTING OR PROGRAM

Not Applicable

BACKGROUND - - FIELD OF INVENTION

This invention relates to a device for measuring fatigue strength and fatigue damage of metallic and composite structures and to a method for predicting the service life remaining on those metallic and composite structures to which the measuring device is attached.

BACKGROUND-- DESCRIPTION OF THE PRIOR ART

Structural and design engineers must be able to determine the fatigue strength and fatigue life of any material that is used or being considered for use as a load-carrying component and which is or will be subjected to a repetitive or cyclic stress loading condition. This requirement stems from the fact that repetitive stress on a structure will eventually cause a material failure in that structure due to fatigue in the material comprising the structure being tested. Further, as a load-carrying structure is subjected to repetitive cyclic loads, structural and design engineers must be able to monitor the effects of these load conditions to determine the remaining service life of the structural member so as to take it out of service before failure occurs.

Engineers have extensively studied the fatigue life of structural materials to more accurately determine the current state of fatigue damage and to more accurately predict the remaining service life in these structures. These studies have shown that fatigue strength is a function of the material comprising the mechanical or metal structure being tested or measured, the manner in which that material has been treated, the ambient temperature in which the structure exists or operates, the amount of stress applied to the structure, and the number of stress cycles the test member undergoes. These studies have also shown that such structures are subject to fatigue failure when they are subjected to repetitive stresses that are lower in magnitude than the ultimate stress of the materials making up the structures being tested. Further, these studies have shown that the service life of a given structural material is inversely proportional to the applied stress; i.e., the greater the applied stress, the shorter the service life of the structural material.

To determine the current state of fatigue damage and/or predict the remaining service life in these structures, test engineers have typically relied upon any number of fatigue monitoring devices such as the fatigue detectors, fuses, gauges, indicators, monitors, predictors, sensors, testers, and transducers taught by the prior art. These conventional devices are typically attached to the structure being monitored so that the test elements are aligned with the direction of the maximum principal stress applied to the structure being tested. As such, these conventional fatigue measuring and/or monitoring devices were capable of monitoring fatigue damage in only one fixed direction. Further, these earlier fatigue gauges typically contained only one test element which necessitated multiple tests on the structure being tested or, alternatively, the attachment of multiple gauges to obtain the desired values of fatigue damage or service life remaining.

Those that contained multiple test elements such as U.S. Patent 3,572,091 issued to McFarland (1971), U.S. Patent 5,319,982 issued to Creager (1994) and U.S. Patent 5,425,272 also issued to Creager (1995) were limited by the costly or time-consuming requirements that the test elements be of the same material as the structure being tested or that the test elements be cracked, notched, or otherwise structurally weakened to ensure that the test element experienced material failure before the structure being tested. Similarly, U.S. Patents 3,786,679 issued to Crites (1974), 4,639,997 issued to Brull (1987), or 5,355,734 issued to Kajino (1994) were limited by the requirement(s) that the test elements be of the same material as the structure being tested or that the test elements be "cracked," "notched," or otherwise structurally weakened to ensure that the test element experienced material failure before the structure being tested.

Those which embodied multidirectional monitoring or indicating devices such

as the device taught by U.S. Patent 6,443,018 B1 issued to Lee et al.(2002) were limited in that they were designed to only measure or monitor structures with different lengths of artificial cracks or structures with a "weak point" such as a welded joint. Other gauges containing multiple test elements such as that taught by U.S. Patent 4,081,993 issued to Leonhardt et al. (1978) were limited in that they were designed to measure compressive stress only.

Structural and design engineers had concerns in the laboratory as well. The relationship between applied stress and service life of any given structural material or component is typically shown by plotting the applied stress ("S") on a structural material or component against the number of cyclic applications ("N") required to induce failure at that particular stress level. In order to obtain the S-N curve of any new material or composite material for which failure data is not available, test engineers have typically fabricated that material or composite into a test element as suggested by the American Society of Testing Materials ("ASTM") handbook. These test engineers would then subject those specimens to cyclic loads of constant magnitude until the specimen failed. This process would then be repeated upon another specimen which would be subjected to repetitive cyclic loads of induced stress of a different magnitude until failure occurred. Test engineers would repeat these tests until they were able to obtain an acceptable number of data points to determine that material's performance under a number of load conditions. These repetitive tests were costly and time-consuming.

Objects and Advantages

The disclosed fatigue measurement device has been designed to solve the foregoing problems found in the prior art. Accordingly, the objects and advantages of

the present invention are to provide a fatigue strength and fatigue damage indicator:

(1) that is capable of measuring fatigue strength and fatigue damage in any direction rather than only along the axis of the applied stress.

(2) that will dramatically reduce the number of tests required to graph the S-N curve for any material or composite material being tested.

(3) that may be constructed of the same material or a material other than that of the structure being tested.

(4) that can be used on new structures as well as structures already in service or having some type of prior stress history.

(5) that can measure expended fatigue life of a structure discretely.

(6) that does not require artificial weakening of the test elements.

(7) that does not require any special training to operate.

(8) that reliably predicts a structure's remaining service life.

(9) that will reduce service depot or down-time of the structure or component being measured.

Further objects and advantages of my invention will become apparent from a consideration of the drawings and the ensuing description of the invention.

SUMMARY

This invention provides an apparatus and method for measuring the multidirectional fatigue strength and fatigue damage of structures and then predicting the service life remaining in the structure tested. The apparatus is a specially designed fatigue gauge that contains multiple breakable ligaments of either variable length to measure fatigue strength or fatigue damage of metallic,

polymeric and composite materials or the same length but different composition to measure the fatigue strength and fatigue damage of certain composite materials.

DRAWINGS

Drawing Figures

FIG. 1 shows one embodiment of a fatigue-test coupon where the ligaments vary in length and surface area.

FIG. 2 shows another embodiment of a fatigue-test coupon where the ligaments do not vary in length or surface area.

FIGS. 3a and 3b show plan and sectional views of a fatigue-test coupon which has been attached to a structure to measure fatigue damage and fatigue strength along the axis of the applied stress.

FIG. 4 shows another embodiment of a fatigue-test coupon where the ligaments vary in length and surface area.

FIG. 5 shows a plan view of another embodiment wherein the fatigue test-coupon has a polygonal configuration and has been attached to a structure to measure multidirectional fatigue damage and fatigue strength.

FIG. 6 shows a typical fatigue life curve generally called the S-N curve wherein S_i and S_{i+1} correspond to applied stress levels and N_i and N_{i+1} correspond to the number of applied load cycles.

Reference Numerals in Drawings

1 - test-coupon
2 - slot S_2
3 - slot S_3
4 - slot S_4
5 - slot S_5
6 - slot S_6
7 - ligament L_7
8 - ligament L_8
9 - ligament L_9
10 - ligament L_{10}
11 - slot S_{11}
12 - ligament L_{12}
13 - ligament L_{13}
14 - ligament L_{14}
15 - ligament L_{15}
16 - slot S_{16}
17 - slot S_{17}
18 - slot S_{18}
19 - slot S_{119}
20 - test structure
21 - bond between coupon and structure
22 - polygonal test-coupon

DETAILED DESCRIPTION

Description

FIG. 1 shows an apparatus for measuring fatigue life and fatigue stress on a monitored structure of known composition. The apparatus shown in FIG. 1 is best described as a test-coupon **1** which can be placed upon a test structure **20** selected for stress-fatigue testing and stress-damage testing.

Test-coupon **1** can be fabricated from any suitable material such as aluminum, titanium, stainless steel, copper, etc. which has been rolled into a thin

sheet of uniform composition and uniform thickness and then placed under a programmable cutting device. Examples of suitable cutting devices include, without limitation, machine-punches, wire cutting machinery, electro-discharge cutting machinery, laser-cutters, or other such cutting devices which have been configured or programmed to map and cut out slots **2, 3, 4, 5, 6** which define ligaments **7, 8, 9, 10**. Typically, computer software associated with any such programmable cutting device will calculate the appropriate dimensions for slots **2, 3, 4, 5, 6** based upon the material from which test-coupon **1** is fabricated.

As mentioned previously, this fatigue measurement device, unlike those taught by the prior art, can be fabricated from any suitable material and, as such, presents a significant advantage over the prior art which typically teaches fatigue measurement devices which must be fabricated from the same material as the structure being tested. The appropriate dimensions for slots **2, 3, 4, 5, 6** will depend upon the material from which test-coupon **1** is fabricated. These dimensions can be calculated by hand and manually entered into a cutting device. These dimensions can also be calculated using computer software associated with and/or part of any such cutting device.

FIG. 1 shows test-coupon **1** with multiple slots **2, 3, 4, 5, 6** defining ligaments **7, 8, 9, 10**. The actual number of slots in test-coupon **1** can vary. This gives a test engineer an opportunity to increase testing efficiency by increasing the number of ligaments and thereby reducing the number of cyclic stress tests necessary to obtain sufficient data.

FIG. 1 shows test-coupon **1** having multiple slots **2, 3, 4, 5, 6** with different configurations or shapes. This gives each slot **2, 3, 4, 5, 6** a different surface area (SSA_2, SSA_3, SSA_4, SSA_5 SSA_6). Accordingly, each ligament **7, 8, 9, 10** on test-

coupon **1** shown in FIG. 1 will have a different length (l_7, l_8, l_9, l_{10}), a different surface area (LSA_7, LSA_8, LSA_9, LSA_{10}), and a different cross-sectional area ($LCSA_7$, $LCSA_8$, $LCSA_9$, $LCSA_{10}$). Because of these variations in dimensions, ligaments **7, 8, 9, 10** will fail due to stress fatigue in sequence from the weakest ligament to the strongest. In this configuration, the dimensions of ligaments **7, 8, 9, 10** are calculated in a manner to ensure that ligaments **7, 8, 9, 10** fail in sequence due to stress fatigue before test structure **20** fails due to stress fatigue when test-coupon **1** and test structure **20** are subjected to substantially the same test history.

As test-coupon **1** is subjected to cyclic stress loads of known or predetermined magnitude, each ligament **7, 8, 9, 10** will experience elongation or contraction equal to that experienced by test structure **20**. Because each ligament **7, 8, 9, 10** has a different length, a different surface area, and a different cross-sectional area, each ligament **7, 8, 9, 10** will experience a different amount of induced stress σ and strain ϵ from the same applied load. These different amounts of induced stress σ and strain ϵ vary as functions of the length and cross-sectional area of ligament **7, 8, 9, 10**. The weakest ligament experiences the greatest amount of induced stress σ and strain ϵ for a given applied load and will fail before the other ligaments in test-coupon **1**. As test-coupon **1** and test structure **20** are subjected to additional cycles of applied loads, the next weakest ligament (which is the next shortest in length) will fail. As additional cycles of applied stress δ are applied, each remaining ligament will fail sequentially from the weakest ligament remaining to the strongest ligament remaining.

FIG. 2 shows another embodiment of the fatigue measurement device wherein all slots **11** have the same shape or configuration and, accordingly, the same surface area (SSA_{11}). As such, all ligaments **12** will have the same length

(l_{12}), surface area (LSA_{12}), and cross-sectional area ($LCSA_{12}$). In the configuration depicted by FIG. 2, the composition of test-coupon **1** would be varied so that the elastic modulus of each ligament **11** would have a different value. As such, the ligament with the highest elastic modulus would fail under cylic loading before other ligaments having lower elastic moduli because the higher elastic modulus induces a higher stress in that particular ligament. Test-coupon **1** might be used for fatigue strength testing and fatigue damage testing in a scenario where more history is available on a test structure **20**. Test-coupon **1** might also be used in this configuration to provide a warning or other indication that test structure **20** has reached a certain milestone in its service life.

The fatigue measuring device depicted by FIG. 2 can also be fabricated from any suitable material and, therefore, also presents a significant advantage over the prior art. The appropriate dimensions for slot **11** and ligament **12** will depend upon the material from which test-coupon **1** is fabricated. These dimensions can be calculated by hand and manually entered into a cutting device. These dimensions can also be calculated using computer software associated with and/or part of any device used for cutting out slot **11**.

FIG. 3a shows a plan view of test-coupon **1** attached to test structure **20**. FIG. 3b shows a cross-section of test-coupon **1** attached to test structure **20**. Any type of securing technique that is compatible with test-coupon **1** and test structure **20** may be used to create bond **21**. Compatible securing techniques include, without limitation, methods such as welding and the use of adhesive bonding compounds.

FIG. 4 shows an embodiment of test-coupon **1** that is a variation of the embodiment depicted in FIG.1. FIG. 4 shows test-coupon **1** having multiple slots

16, 17, 18, 19 with different configurations or shapes that have been cut or fabricated using a stepped template. This gives each slot **16, 17, 18, 19** a different surface area (SSA_{16}, SSA_{17}, SSA_{18}, SSA_{19}). Accordingly, each ligament **13, 14, 15** on test-coupon **1** shown in FIG. 4 will have a different length (l_{13}, l_{14}, l_{15}) a different surface area (LSA_{13}, $LSA_{14,}$ LSA_{15}), and a different cross-sectional area ($LCSA_{13}$, $LCSA_{14,}$ $LCSA_{15}$).

Because of these variations in dimensions, ligaments **13, 14, 15**, like those depicted in FIG. 1, will fail due to stress fatigue in sequence from the weakest ligament to the strongest. In this configuration, the dimensions of ligaments **13, 14, 15** are calculated in a manner to ensure that ligaments **13, 14, 15** fail in sequence due to stress fatigue before test structure **20** fails due to stress fatigue when test-coupon **1** and test structure **20** are subjected to substantially the same test history.

The use of a stepped template to cut slots **16, 17, 18, 19** gives the test engineer more control in ordering small-scale variations in the dimensions of slots **16, 17, 18, 19**. While the configuration shown in FIG. 1 would typically be used to measure and monitor fatigue stress and fatigue damage over a large range of values, the configuration depicted in FIG. 4 would typically be used to measure and monitor fatigue stress and fatigue damage over a much narrower range of values, thereby giving the test engineer a more accurate picture of a critical range of values.

FIG. 5 shows the preferred embodiment of the invention whereby a differently configured test-coupon **22** is used for measuring stress fatigue and stress damage when the principal loading direction is unknown or when the principal loading direction changes as a function of time. The shape of test-coupon **22** can be a polygon or a circle. By increasing the number of sides on a polygonal test-coupon **22**, a test engineer can increase the number of axes or directions along

which stress fatigue and stress damage can be measured and thereby increase the accuracy of the measurements.

FIG. 6 shows a typical fatigue life curve generally called the S-N curve wherein S_i and S_{i+1} correspond to applied stress levels and N_i and N_{i+1} correspond to the number of applied load cycles for failure. Any material used to fabricate structural members or the apparatus contemplated by this disclosure will have a unique fatigue life curve which provides an indication of the number of load cycles which will induce fatigue failure as a function of the applied stress. Accordingly, the representative material to which the S-N curve depicted by Figure 6 applies will experience failure due to stress fatigue if it is subjected to a level S_i for N_i cycles. Similarly, this same material will experience failure due to stress fatigue if it is subjected to a different level of stress, S_{i+1} for a different number, N_{i+1}, cycles. The shape of the S-N curve more accurately reflects the fatigue life of the material being tested as the number of different values of induced stress increases because more data points are available to the test engineer.

Operation

The fatigue measuring device relies upon the principle that any given material subjected to cyclic stress loads of known magnitude will eventually experience failure due to stress fatigue at a predetermined point; i.e., a known number of repetitive loading cycles. If the magnitude of the cyclic stress load is changed, that given material will experience failure due to stress fatigue after a different number of repetitive loading cycles.

In operation, test-coupon **1** is mounted on test structure **20** and located in such a manner as to experience the same strain history and environment as that

experienced by test structure **20**. Attachment of test-coupon **1** to test structure **20** can be accomplished by means of pins, adhesive bonds or welding. Unlike most of the test-coupons taught by the prior art, test-coupons **1** does not need to be mounted at any critical location of test structure **20**. However, test-coupon **1** should be mounted in such a manner so as to experience the same strain history and environment as test structure **20**. Typically, the axis of test-coupon **1** is oriented in the direction of maximum principal tensile strain which is anticipated on test structure **20**.

As test-coupon **1** is subjected to cyclic stress loads of known or predetermined magnitude, each one of ligaments **7, 8, 9, 10** will experience the same amount of elongation or contraction as test structure **20**. Because each ligament **7, 8, 9, 10** has a different length and cross-sectional area, each ligament **7, 8, 9, 10** will experience a different amount of induced stress σ and strain ϵ from the same applied load. These different amounts of induced stress σ and strain ϵ are vary as functions of the length and cross-sectional area of ligament **7, 8, 9, 10**. The weakest ligament experiences the greatest amount of induced stress σ and strain ϵ for a given applied load and will fail before the remaining ligaments. As test coupon **1** and structure being tested **20** are subjected to additional cycles of an applied load, the next weakest ligament will fail. As additional cycles of an applied load are experienced by test coupon **1** and structure being tested **20**, each remaining ligament will fail sequentially from the weakest remaining ligament to the next-weakest remaining ligament and so on until all ligaments have failed.

For example, compare ligament 7 to ligament **10** on test-coupon **1** as depicted in FIG. 1. The overall length of ligament 7 (l_7) is the sum of the lengths of the upper portion of ligament 7 (l_{7u}) and the lower portion of ligament 7 (l_{7l}); the

length of ligament **10** is (l_{10}). Similarly, the cross-sectional area of ligament **7** is broken down into two components: that of the upper portion of ligament **7** (CSA_{7u}) and that of the lower portion of ligament **7** (CSA_{7l}); the cross-sectional area of ligament **10** is (CSA_{10}). When both ligaments **7, 10** have the same displacement δ, the strain or stress ratio for ligaments **7, 10** is:

$$\varepsilon_{7u} / \varepsilon_{10} = \sigma_{7u} / \sigma_{10} = (CSA_{7l}\, L_{10})/(CSA_{7u}\, L_{7l} + CSA_{7l}\, L_{7u})$$

where ε_{7u} is the strain in the upper portion of ligament 7, ε_{10} is the strain in ligament **10**, σ_{7u} is the stress in the upper portion of ligament **7** and σ_{10} is the stress in ligaments **10**. If $L_{7u} = L_{7l} = L_{10}/2$ and $CSA_{7u} = CSA_{7l}/2$, then the strain and the stress in the upper portion of ligament **7** are 1.3 times larger than those found in ligament **10**. Accordingly, ligament **7** will fail earlier than ligament **10** because it is under the highest strain and stress. By proper combination of the variable properties of ligaments, **7, 8, 9, 10,** the induced stress and strain ratios of all ligaments **7, 8, 9, 10** can be determined for a given displacement. In general, each ligament **7, 8, 9, 10** may have multiple ligament portions or sections of different lengths and cross-sectional areas. Controlling the lengths and cross-sectional areas will permit the test engineer to to achieve his desired ratios of induced stress and induced strain for each ligament **7, 8, 9, 10** portion or section.

The induced stress ratio and induced strain ratio will determine when each ligament **7, 8, 9, 10** will fail under fatigue loading. The ligament with the highest stress will fail first, followed by the ligament with the next highest stress, and so on. Careful design of ligaments **7, 8, 9, 10** in test coupon **1** will permit discrete determination of present service life of test structure **20**. More ligaments on test-coupon **1** will permit the test engineer to determine service life in smaller (more accurate) intervals.

In laboratory operation, test engineers would typically use the device shown in FIG. 1 to obtain the data points necessary to plot the S-N curve for a new material. Test-coupon **1** is fabricated using the new material and then subjected to cyclic load testing. A given load condition ("S") is plotted on the vertical axis of the S-N curve while the number of cycles ("N") required to cause failure at that given load condition is plotted on the horizontal axis. A second load condition ("S+1") is then plotted on the vertical axis while the number of cycles (N+1) required to cause failure at that different load condition (S+1) is plotted on the horizontal axis. The test engineer will plot enough data points to determine service life under whatever range of loading conditions are mandated by the anticipated use of the material being tested.

The reader should note that using the test-coupon **1** depicted in FIG.1 will permit test engineers to obtain multiple data points on the S-N curve from a single fatigue cycle loading test. The number of data points on a given S-N curve will correspond to the number of ligaments in a test coupon. Increasing the number of ligaments will increase the number of data points on the S-N curve and thereby, increase its utility over a greater range of values. This aspect of this invention is a significant improvement over the prior art which required multiple fatigue cycle loading tests to obtain sufficient data points on the S-N curve.

Otherwise, test structure **20** is selected or identified for stress-fatigue testing and stress-damage testing. The stress history of test structure **20** is entered on the S-N curve applicable to the material of which test structure **20** is composed. For example, if test structure **20** is composed of aluminum, the number of stress cycles ("N") to which test structure **20** had been subjected as of the test date would be entered on the horizontal axis of the S-N Curve for aluminum. For any given

loading condition, the number of cycles remaining ("N_R")would be determined by locating the point on the aluminum S-N curve that corresponds to the given or anticipated loading condition ("S_A") and reading off the horizontal axis the corresponding number of cycles at which failure would occur ("N_A"). The difference between "N_A" and "N" is the remaining service life of test structure **20**.

Conclusion, Ramifications, and Scope

Accordingly, the reader will see that the invention described above provides single-directional and multi-directional fatigue measurement devices which are capable of measuring the actual degree of fatigue damage more accurately and more efficiently than those taught by the prior art. The invention described above provides numerous additional advantages over those taught by the prior art, including, without limitation:

* This device is capable of measuring fatigue strength and fatigue damage in any direction as well as along the axis of the applied stress.
* This invention will save time and money for test engineers because:
    (1) it will dramatically reduce the number of tests required to graph the S-N curve for any material or composite material being tested.
    (2) it does not require artificial weakening of the test elements.
    (3) it does not require any special training to operate.
    (4) it reliably predicts a structure's remaining service life.

* Accordingly, this invention will reduce service depot or down-time of the structure or component being measured.
* This invention provides the test engineer with greater flexibility because:
  (1) the test coupon(s) may be constructed of the same material or a material other than that of the structure being tested.
  (2) it can be used on new structures as well as structures already in service or having some type of prior stress history.
  (3) it can measure expended fatigue life of a structure discretely.

Although the description above contains many specificities, these should not be interpreted as limiting the scope of the invention but as merely providing illustrations of some of the presently preferred embodiments of this invention. Those skilled in the art will appreciate that various modifications, additions, and substitutions are possible without departing from the scope and spirit of the invention as disclosed in the accompanying claims. Accordingly, the scope of the invention should be determined by the accompanying claims and their legal equivalents, rather than by the examples given.